# Effect of DEM Resolutions in the Runoff and Soil Loss Predictions of the WEPP Watershed Model

T. A. Cochrane, D. C. Flanagan

**Abstract.** *Erosion prediction utilizing digital elevation models (DEMs) is a logical advancement for automating the simulation process for models such as the Water Erosion Prediction Project (WEPP). The effects of using different DEM resolutions on watershed simulations and the ability to accurately predict sediment yield and runoff from different rainfall event sizes were studied using three application methods and data from six research watersheds. Simulating watersheds with a range of resolutions can help address the problem of deciding what topographic DEM resolution is ideal for model simulations of the watershed outlet, the end of each hillslope, and along the slope profiles. The three application methods studied here were: (1) Hillslope − Chanleng, (2) Hillslope − Calcleng, and (3) Flowpath. The two Hillslope methods use a representative slope profile to represent each hillslope in the watershed, and the Flowpath method uses all of the individual flowpaths as model input for WEPP simulations. Results show that the Hillslope methods were not significantly influenced by DEM resolutions; however, there was an observable interaction between resolutions and the Flowpath method. Large rainfall events were predicted better than small events, but fine DEM resolutions did not improve predictions of either large or small rainfall events. Using coarse DEM resolutions for the topographic input will not decrease the accuracy of erosion prediction using the WEPP model and the Hillslope methods, unless the coarseness of the DEM compromises the delineation of the watershed or hillslopes.*

***Keywords.*** *Digital Elevation Models, Geographic information systems, Soil erosion modeling, Water Erosion Prediction Project.*

In past studies by Cochrane and Flanagan (1999), two general methods have been developed to integrate digital elevation models (DEMs) with the Water Erosion Prediction Project (WEPP) erosion model (Flanagan and Nearing, 1995). These methods have been named the Hillslope methods and the Flowpath method. The two Hillslope methods (Chanleng and Calcleng) consist of the discretization of the watershed into representative hillslopes and channels from a DEM (Cochrane and Flanagan, 2003). In the Hillslope approaches, a channel network is extracted from the DEM using the concept of a critical source area (Garbrecht and Martz, 1997). Hillslopes are then defined as the areas that drain to the right, left, or top of each of the channel segments. A representative hillslope profile is also created for each hillslope from the DEM. The actual representative hillslope profile created by the Chanleng and Calcleng methods is derived in the same way; however, they differ in how the representative hillslope length is calculated. In the Calcleng method, a representative hillslope length is calculated by a method of weighting flowpath lengths and flowpath drainage areas (Cochrane and Flanagan, 2003). This same weighting procedure is used for hillslopes draining to the top of channels in the Chanleng method; however, the lengths of representative hillslopes are calculated differently for hillslopes draining to the sides of channels. In the Chanleng method, for hillslopes adjacent to a channel, the representative hillslope width is set to equal the channel length and the hillslope length is calculated by dividing the total area of the hillslope by its set width. WEPP is then applied to the hillslopes and channel structure in a watershed model simulation.

The Flowpath method consists of applying WEPP to all possible flowpaths in the watershed. Flowpaths are defined in terms of DEM grid cells starting at a point where no other cell in the grid flows into it, and then following through a path defined by individual grid flow vectors, and ending when it reaches a channel. Interactions with other flowpaths are frequent, and soil loss results from the application of WEPP to each flowpath are weighted with the interactions of other flowpaths. However, since there are many flowpaths draining at distinct points along the channels, the WEPP channel routines cannot be used. The current WEPP channel routines are limited in the number of channel segments that can be simulated and limited conceptually in the way runoff and sediment entering from hillslopes are distributed along the channel. Consequently, WEPP simulation results for the Flowpath method can only show sediment loss and runoff from each hillslope or the spatial distribution of soil loss and deposition across all flowpaths in a watershed.

The two Hillslope methods and the Flowpath method predicted runoff and sediment yield comparable to measured data for the six watersheds studied, using DEMs of the finest resolution available (Cochrane and Flanagan, 1999, 2003). It is now important to determine if these methods are accept-

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able when using DEMs degraded to coarser resolutions. There are three different levels to which these simulations can be applied: (1) sediment yield and runoff from the watershed outlet, (2) sediment yield and runoff from the hillslopes (delivery to channels from hillslopes), and (3) soil loss along the actual hillslopes. Therefore, a primary objective of this study was to determine the effect of DEMs of different resolutions on simulation results for the different levels.

Originally, it was hypothesized that model predictions using the finest resolution DEMs would best match the observed runoff and sediment loss data. This hypothesis was reinforced by recent studies by Wang et al. (2002) and Gertner et al. (2002), showing the possible error propagation and uncertainty of DEM resolutions in determining the Revised Universal Soil Loss Equation (RUSLE; Renard et al., 1997) LS factor. In these studies, a coarser resolution DEM of 30 m was interpolated to finer resolutions of 20, 10, and 5 m using a regularized spline with tension and a smoother interpolating technique developed by Mitášová and Mitáš (1993). The results from this study showed that the coarse resolutions led to extremely large predicted values and variances of upslope contributing areas and therefore large uncertainties in LS. They also recommended that DEMs be interpolated to finer resolutions, which would diminish this uncertainty. However, since the calculation methods used to obtain the RUSLE LS factor are very different from the WEPP automated methods of calculating representative slope profiles, the observed uncertainties may or may not be relevant to WEPP simulations for the different resolutions.

The most practical reason to study the effects of using coarser resolutions for watershed modeling is the economical aspect of DEM creation. DEMs can be developed or obtained from a variety of sources that include field surveys, contour maps, aerial or satellite photogrammetry, geographic positioning systems (GPS), laser surveys, and the shuttle radar topography mission (SRTM). However, the cost of creating DEMs of finer resolutions can be high (Renschler et al., 2003). The time required to develop very accurate DEMs for large areas can also be a problem if simulations need to be done quickly. Both economics and development time to create DEMs play a practical role in studying the effects of using different resolutions. However, the DEM resolution required may also be dependent on the level of detail needed by the user. For example, a hydrologist may only be interested in sediment yield coming from a watershed outlet. It is conceivable that for this case a coarser resolution may provide reasonable simulation results, whereas the same resolution may not be sufficient for a conservation specialist who is interested in soil loss along the hillslopes within the watershed. Defining which DEM resolutions are appropriate to produce accurate WEPP simulations for the level of the users' needs can therefore make a unique contribution to the practical application of erosion modeling.

Scientifically, it is also important to study the effects of resolution on the predictions of erosion. Changing resolution will change the slopes and the distribution of flowpath lengths, which may have a substantial effect on the prediction of erosion using WEPP with GIS and DEMs. It is important to document and analyze these effects as they may have a substantial influence on how we may model erosion in the future, especially when dealing with 3−dimensional topography.

Changes in DEM resolution were also expected to have an effect on the ability to simulate different rainfall event sizes. It was believed that the accuracy of simulation results is dependent on the size of the event; the larger the event size, the better the simulation. Larger events have higher peak runoff rates, flow shear stress, and sediment transport capacity and are therefore less influenced by small changes in slope, as could occur when resolution is changed (Nearing, 1998). Small events, however, would be more affected by slope and length. Changes in scale of erosion processes from interill to rill, as occur when simulating small events, are more difficult to predict accurately. Therefore, another objective was to determine if there were any interactions between rainfall event size range and DEM resolution for watershed simulations.

# Materials and Methods

## Experimental Setup: Watersheds and Measured Data

Six research watersheds were selected for this study in three regions of the country. These watersheds are called Treynor W2, near Treynor, Iowa (Kramer, 1993); Watkinsville P1 and P2, near Watkinsville, Georgia; and Holly Springs WC1, WC2, and WC3, near Holly Springs, Mississippi (Liu et al., 1997). A detailed description of the soil, climatic, and land use properties of these watersheds is presented in Cochrane and Flanagan (1999). All simulations of these watersheds were conducted with WEPP version 98.4.

The most important data layer used for discretizing watershed components is the elevation map. Topographic information for the Treynor watershed was obtained by aerial surveys with ground controls. It was determined that the error of surveying was within 18 cm (7 in.) vertical for the ground control sample points. Using these ground control points and aerial photogrammetry, an accurate digital surface map was developed and a grid−based DEM for Treynor watershed W2 was then created. The Arc/Info GIS (ESRI, 2003) was used to create the grid−based DEMs for the required resolutions in this study.

Elevation data for the Holly Springs WC1, WC2, and WC3 watersheds were available from contour−based topographic maps (USDA−ARS, 2003). These contour maps were created from field surveys that were accurate enough to create 1.52 m contours. Vertical accuracy of these maps is believed to comply with USGS map accuracy standards, which states that not more that 10% of random points tested have a vertical error of more than one−half the contour interval. The contour maps were digitized and transformed to DEMs. Topographic data for the Watkinsville P1 and P2 watersheds were available in the form of contour maps with 0.5 m contour intervals, which were transformed to grid−based DEMs at the required resolutions for the study.

Measured runoff and sediment yield values for each watershed were available on an event−by−event basis and are summarized in table 1. All watersheds were simulated in the same manner as in Cochrane and Flanagan (1999), except for the Watkinsville P1 watershed. The topography of watershed P1 was unchanged during the 11 years of study, but the cropping and management practices allowed the watershed to be divided into two different simulation periods: before and after conservation practices were installed. Between

**Table 1. Measured mean event data values for each watershed.[a]**

| Water− shed | No. of Events | Mean Rainfall (mm/event) | Mean Runoff (mm/event) | Mean Sediment Yield (T/ha/event) |
|---|---|---|---|---|
| WC1 | 284 | 27.2 (18.68) | 13.098 (16.252) | 0.234 (2.059) |
| WC2 | 257 | 28.4 (19.14) | 15.014 (18.125) | 0.263 (2.377) |
| WC3 | 255 | 28.8 (18.98) | 10.695 (14.810) | 0.182 (1.108) |
| P1a | 36 | 37.6 (27.68) | 12.972 (16.631) | 1.769 (3.674) |
| P1b | 31 | 50.2 (26.26) | 8.516 (12.790) | 0.015 (0.025) |
| P2 | 55 | 30.5 (23.69) | 7.800 (14.687) | 0.335 (1.237) |
| W2 | 40 | 32.8 (25.08) | 5.140 (7.375) | 1.018 (2.426) |

[a] Mean values with standard deviations in parentheses.

1972 and 1974, the watershed was under a continuous tillage cropping management and there were no conservation practices implemented. After 1974, conservation practices such as grassed waterways (fescue grass) and zero tillage were implemented, which drastically changed the runoff and sediment yields from the watershed. For simulation purposes, two unique sets of hillslope and channel parameters were created: P1a (before conservation) and P1b (after conservation).

### Resolution and Its Effects on Slope and Flowpath Length

In order to study the effects of a variety of resolutions on WEPP simulations, the DEM resolutions of the Holly Springs and Watkinsville watersheds were degraded from the original 1 m raster by using a nearest−neighbor raster aggregation procedure in Arc View (ESRI, 2003). The resulting resolutions for these small watersheds were 1, 3, 5, and 10 m. These sizes were chosen to offer a wide range between the finest DEM and the coarsest DEM possible. A resolution greater than 10 m was not possible because the definition of the boundary of the watersheds became compromised. DEM resolutions of 5, 10, 15, and 20 m were created for the Treynor watershed using the Arc Info lattice commands (ESRI, 2003). Coarser resolutions for this watershed were possible, but the correct definition (size and shape) of the watershed also became somewhat compromised. Since the Holly Springs and Watkinsville watersheds are significantly different in size compared to the Treynor watersheds (table 2), the resolution sizes have been categorized into very fine, fine, medium, and coarse for all the watersheds. This categorization was based on the relative size of the watersheds as related to the derived resolutions.

### Event Sizes and Resolution

Knowing the relationship between input event sizes and resolution is important for both the model users and developers. If the accuracy of the simulation for different size

**Table 2. DEM grid resolutions studied for each watershed.**

| Watershed | Area (ha) | Resolution (m) Very fine | Fine | Medium | Coarse |
|---|---|---|---|---|---|
| Treynor W2 | 29 | 5 | 10 | 15 | 20 |
| Watkinsville P1a | 2.70 | 1 | 3 | 5 | 10 |
| Watkinsville P1b | 2.70 | | | | |
| Watkinsville P2 | 1.29 | | | | |
| Holly Springs WC1 | 1.57 | | | | |
| Holly Springs WC2 | 0.59 | | | | |
| Holly Springs WC3 | 0.65 | | | | |

**Table 3. Input rainfall event size distribution and measured data values for each distribution range.**

| | Rainfall Range (mm/event) | No. of Events | Mean Rainfall (mm/event) | Mean Runoff (mm/event) | Mean Sediment Yield (T/ha/event) |
|---|---|---|---|---|---|
| Small | 0.0 − 15.9 | 242 | 11.35 | 3.40 | 0.070 |
| Medium | 16.0 − 23.9 | 249 | 19.89 | 6.10 | 0.167 |
| Large | 24.0 − 36.9 | 231 | 29.63 | 9.77 | 0.197 |
| Very large | 37.0 − 113 | 236 | 58.23 | 29.97 | 0.845 |

events is affected by DEM resolution, a user or researcher may try to use historical rainfall events as a basis to selecting an appropriate DEM resolution for topographic input to the model.

To address this issue, simulations were conducted using an event classification based on input rainfall. Rainfall event data from the watersheds, which numbered 906 events, were divided into four ranges (small, medium, large, and very large), as shown in table 3. The rainfall ranges were selected based on a balanced distribution of the number of events for the watersheds. The measured output event range data values for rainfall, runoff, and sediment yields are shown for reference purposes.

### Statistical Analysis

A statistical analysis was conducted to evaluate the watershed simulations with different resolutions, event size ranges, and methods (Hillslope methods: Chanleng and Calcleng, and Flowpath method). The analysis was carried out using daily event runoff and sediment yields from the outlet of each research watershed, which were transformed to express values in runoff depth in millimeters and sediment yield per area in tonnes per hectare per event. Due to the number of variables and large quantity of data, an analysis of variance (ANOVA) was deemed appropriate to test for all conditions and interactions between resolutions and methods. Multiple comparison tests such as Duncan's and Tukey's methods were used to compare simulation results with different DEM resolutions levels.

Linear regressions were used to compare the goodness of fit ($R^2$) between measured data and each of the resolutions and event ranges. The closer the $R^2$ value is to 1.0 the better is the fit between the measured data and the simulated data. The difference in $R^2$ values between simulations using the different resolutions can also indicate whether one resolution level produces WEPP model predictions with better results than another. Higher $R^2$ values indicate a better simulation for the specific resolution level. The Nash−Sutcliffe model efficiency coefficient (Nash and Sutcliffe, 1970) was also used to compare measured and simulated results. The Nash−Sutcliffe coefficient approaches unity as the fit between measured and simulated values improves. A value of one indicates a perfect fit.

T−tests were used to show whether there was a significant difference between the measured and simulated means of either sediment yield or runoff, and in turn to compare these results at different resolution levels. An alpha level of 0.01 (confidence interval of 99%) was used for all T−tests to determine whether the difference between means of one set of data events and another was equal to zero or not. T−values greater than the critical T−value indicate that there was a significant difference between means at the 0.01 alpha level.

Table 4. Watershed slope values for Treynor W2 watershed.

| | Resolution | | | |
|---|---|---|---|---|
| | 5 m | 10 m | 15 m | 20 m |
| Average slope | 0.07034 | 0.06817 | 0.06790 | 0.06675 |
| Standard deviation | 0.03703 | 0.03424 | 0.03234 | 0.03138 |
| Minimum slope | 0.00001 | 0.00707 | 0.00471 | 0.00354 |
| Maximum slope | 0.33996 | 0.21000 | 0.18667 | 0.16000 |

# Results and Discussion

## Changes in DEM Resolution

Changes in the resolution of the DEM affect the slopes and distribution of slopes within watersheds. The average slope, standard deviation, and maximum slope values decrease while the minimum slope value increases as the DEM resolution becomes coarser. This simply reinforces the observation that an averaging of elevations and slopes occur as resolution is degraded, although the overall spatial distribution remains similar. In other words, a smoothing of the topographic features of the watershed occurs when DEM resolution is coarser. An example of DEM−derived slope values for the Treynor W2 watershed can be seen in table 4. Slope values are derived from the relationship of each DEM grid cell to its neighbor, which can cause high slope values for some individual cells as observed in the high values for maximum slope in the finer 5 m resolution. Average slope decreased about 5% and maximum slope decreased over 50% between very fine and coarse resolutions. Similar results were observed for the other watersheds.

The area or boundary of the watershed slightly changes between the different resolutions. For example, small changes in the boundary of the Watkinsville P2 watershed and its hillslopes can be observed in figure 1. Similarly, small changes in the representation of the hillslopes are obvious, as can be observed by the change in shape of the top hillslope between the 1 m resolution and the 10 m resolution DEM. A coarser resolution than 10 m for this watershed caused significant changes to the watershed area and shape of the hillslopes and therefore would not have been representative of the original watershed and hillslopes.

A comparative analysis of the DEMs used for watershed modeling in this study shows that the number of flowpaths in fine resolution DEMs is larger than the number of flowpaths in a coarse DEM. It was also observed that the flowpath length increases as resolution becomes coarser, but the standard deviation of the flowpath lengths decreases. A typical example of this is presented in figure 2 for the distribution of flowpath lengths for different DEM resolutions of the Watkinsville P2 watershed.

Even though sensitivity studies have been carried out for the WEPP model on the individual slope and slope lengths parameters (Baffaut et al., 1997; Nearing et al., 1990), the complex interactions observed between the changes in DEM slopes, flowpaths lengths, and changes in hillslope shapes can only be quantified by experimentation using actual watersheds and DEMs. With comparisons between simulations and between measured data and simulation results, we can thus determine if changes in resolution affected the overall results and at what level, and whether changes in resolution affected the watershed outlet results, the hillslope results, or soil loss along the hillslope profiles.

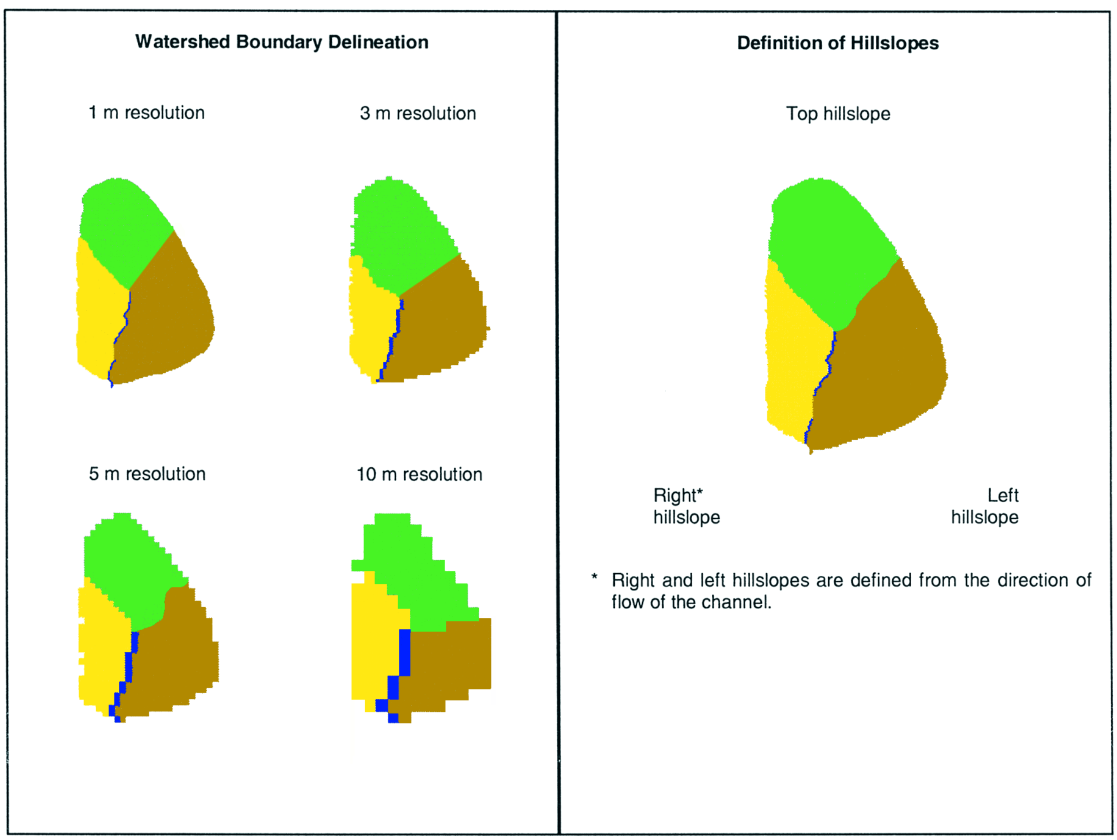


Figure 1. Watershed and hillslope boundary delineation of Watkinsville P2 watershed as affected by DEM resolution.

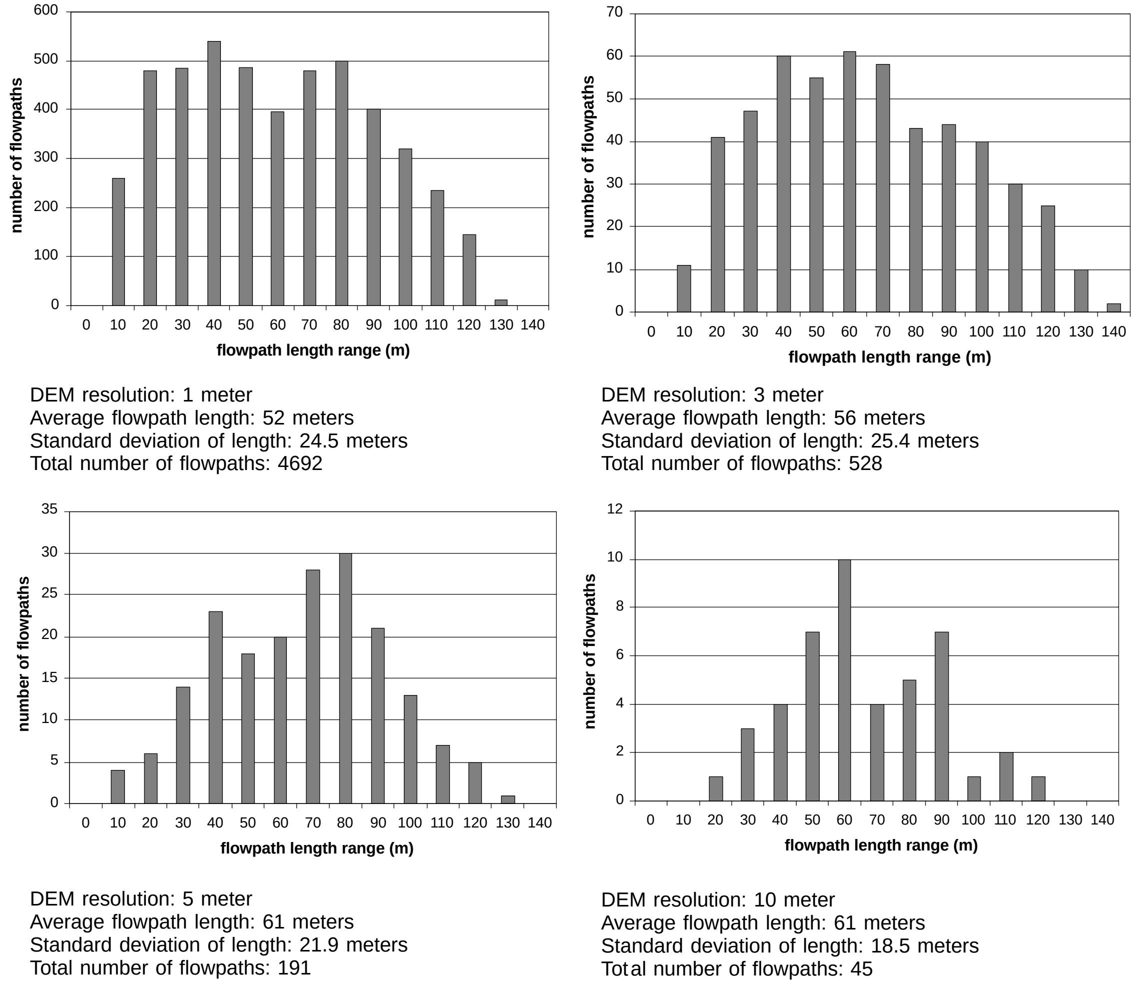


**Figure 2. Distribution of flowpath lengths at different resolutions for Watkinsville P2 watershed.**

### WATERSHED OUTLET RESULTS

The results for sediment yield and runoff from the outlets of the watersheds showed that the range of DEM resolution used for the WEPP watershed simulations did not have a consistently significant effect on the prediction of runoff and sediment yield. The prediction of sediment yield from watersheds was not consistently better with finer DEM resolutions, as can be seen in the results presented in tables 5 and 6.

Analysis of variance between simulated sediment yield results using the different DEM resolutions showed no significant statistical differences, as illustrated by the multiple comparisons groupings done with both Duncan's and Tukey's statistical methods (table 5). Furthermore, linear regression goodness of fit values ($R^2$) between simulated and measured sediment yield were not significantly different between resolutions, as seen in table 5 and figure 3. In figure 3, where resolution is plotted versus $R^2$ for each method using all events from all the watersheds, there are no observable differences between resolution levels, although there is a difference between the goodness of fit values for the Flowpath method (0.657 to 0.674) and the Hillslope methods (0.698 to 0.711).

The Nash−Sutcliffe (N−S) model efficiency coefficients in table 6 show that there was little difference between DEM resolution simulations for runoff. N−S coefficients for sediment yield displayed mixed results for some watersheds; however, finer resolutions were not consistently better than coarser resolutions. In watershed P1b, large negative N−S coefficients were calculated due to overprediction of sediment yield, which was possibly due to additional conservation practices implemented in the field but not comprehensively included in the model input management files.

The results in tables 5 and 6 show that the Hillslope methods did a better job of matching the predicted sediment loss with the observed values than the Flowpath method. This was expected because the Flowpath simulations neglect sediment contributions from the channel (Cochrane and Flanagan, 2003).

Regression results for the runoff simulations are not displayed here, but they clearly showed that DEM resolution did not have a significant effect on runoff predictions. Coefficients of determination ($R^2$) between measured and simulated runoff only varied from 0.755 to 0.759 between resolutions for all methods.

Further analysis of the watershed sediment yields showed that there were observable differences in how resolution affected the methods. A comparison of mean sediment yield event values showed that there was an observable increase in mean values with coarse DEM resolutions, an example of which can be seen for the Flowpath method in table 5 and figure 4. The T−values in figure 4, which show a statistical comparison

Table 5. Summarized watershed outlet simulated sediment yield results in T/ha/event.

| | DEM Res. (m) | DEM Area (ha) | Mean Predicted Sediment Yield for Each Method (T/ha/event) | | | | Combined Predicted Sediment Yield (T/ha/event) | | Goodness of Fit between Measured and Simulated[a] ($R^2$) | ANOVA Statistical Grouping[b] |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Measured | Calcleng | Chanleng | Flowpath | Mean | Std. | | |
| WC1 | 1 | 1.580 | 0.234 | 0.534 | 0.556 | 0.735 | 0.608 | 3.322 | 0.789 | A |
| | 3 | 1.589 | | 0.538 | 0.567 | 0.799 | 0.634 | 3.501 | 0.789 | A |
| | 5 | 1.625 | | 0.524 | 0.535 | 0.785 | 0.615 | 3.413 | 0.787 | A |
| | 10 | 1.470 | | 0.546 | 0.513 | 0.855 | 0.638 | 3.522 | 0.789 | A |
| WC2 | 1 | 0.593 | 0.263 | 0.480 | 0.477 | 0.596 | 0.518 | 2.537 | 0.798 | A |
| | 3 | 0.588 | | 0.478 | 0.464 | 0.614 | 0.519 | 2.584 | 0.798 | A |
| | 5 | 0.588 | | 0.527 | 0.513 | 0.726 | 0.588 | 2.928 | 0.796 | A |
| | 10 | 0.590 | | 0.519 | 0.456 | 0.753 | 0.576 | 2.899 | 0.795 | A |
| WC3 | 1 | 0.637 | 0.182 | 0.260 | 0.242 | 0.298 | 0.267 | 1.326 | 0.567 | A |
| | 3 | 0.631 | | 0.302 | 0.282 | 0.402 | 0.329 | 1.730 | 0.573 | A |
| | 5 | 0.633 | | 0.298 | 0.279 | 0.430 | 0.336 | 1.807 | 0.571 | A |
| | 10 | 0.630 | | 0.281 | 0.249 | 0.441 | 0.324 | 1.721 | 0.577 | A |
| P1a | 1 | 2.897 | 1.769 | 1.546 | 1.513 | 0.959 | 1.339 | 3.329 | 0.531 | A |
| | 3 | 2.925 | | 1.543 | 1.466 | 1.044 | 1.351 | 3.326 | 0.530 | A |
| | 5 | 2.968 | | 1.520 | 1.411 | 1.128 | 1.353 | 3.350 | 0.535 | A |
| | 10 | 3.020 | | 1.572 | 1.430 | 1.211 | 1.405 | 3.416 | 0.520 | A |
| P1b | 1 | 2.897 | 0.015 | 0.102 | 0.099 | 0.054 | 0.085 | 0.148 | 0.158 | A |
| | 3 | 2.925 | | 0.106 | 0.109 | 0.083 | 0.099 | 0.176 | 0.140 | A |
| | 5 | 2.968 | | 0.106 | 0.108 | 0.092 | 0.102 | 0.180 | 0.142 | A |
| | 10 | 3.020 | | 0.104 | 0.105 | 0.097 | 0.102 | 0.181 | 0.144 | A |
| P2 | 1 | 1.556 | 0.335 | 0.333 | 0.339 | 0.199 | 0.290 | 0.911 | 0.889 | A |
| | 3 | 1.555 | | 0.274 | 0.270 | 0.236 | 0.260 | 0.881 | 0.909 | A |
| | 5 | 1.580 | | 0.279 | 0.276 | 0.263 | 0.273 | 0.930 | 0.913 | A |
| | 10 | 1.580 | | 0.330 | 0.310 | 0.344 | 0.328 | 1.057 | 0.905 | A |
| W2 | 5 | 30.175 | 1.018 | 1.300 | 1.193 | 1.218 | 1.237 | 2.712 | 0.628 | A |
| | 10 | 30.350 | | 1.302 | 1.221 | 1.277 | 1.267 | 2.834 | 0.634 | A |
| | 15 | 29.318 | | 1.354 | 1.204 | 1.399 | 1.319 | 2.905 | 0.634 | A |
| | 20 | 30.520 | | 1.447 | 1.364 | 1.513 | 1.441 | 3.254 | 0.647 | A |

[a] Linear regression goodness of fit factor ($R^2$) between measured and simulated sediment yield events.
[b] ANOVA comparisons with Tukey's and Duncan's statistical methods showing no difference between resolutions.

between measured and simulated means, are low for the very fine resolution and progressively higher for the fine and medium resolutions, and finally overcome the critical T−value at the coarse resolution. This illustrates that at the coarse resolution the mean sediment yield event value is significantly different from the measured mean value. This difference is minimal for the Calcleng and Chanleng methods, implying that the Flowpath method is more sensitive to input DEM resolution than the Hillslope methods.

In summary, the simulations using DEM data at fine resolution levels did not have significantly better results than those using data at coarse resolution levels. Changes in slopes

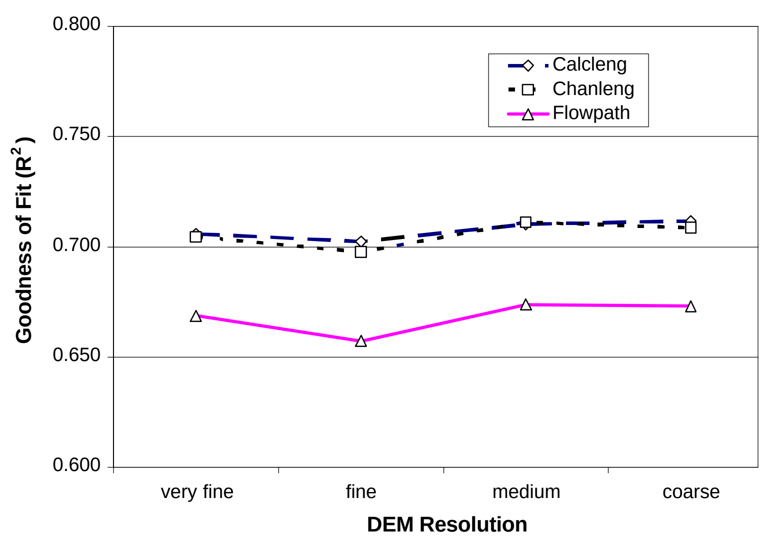


Figure 3. Comparisons of linear regression goodness of fit ($R^2$) between measured and simulated sediment yield events for different DEM resolutions.

Table 6. Nash−Sutcliffe model efficiency coefficients for comparisons between measured and simulated runoff and sediment yield from watershed outlets.

| | DEM Res. (m) | Runoff | | | Sediment Yield | | |
|---|---|---|---|---|---|---|---|
| | | Calcleng | Chanleng | Flowpath | Calcleng | Chanleng | Flowpath |
| WC1 | 1 | 0.70 | 0.70 | 0.69 | 0.54 | 0.48 | −0.64 |
| | 3 | 0.70 | 0.70 | 0.69 | 0.52 | 0.44 | −1.18 |
| | 5 | 0.70 | 0.70 | 0.69 | 0.55 | 0.52 | −1.14 |
| | 10 | 0.69 | 0.69 | 0.67 | 0.51 | 0.60 | −1.72 |
| WC2 | 1 | 0.70 | 0.69 | 0.68 | 0.78 | 0.78 | 0.59 |
| | 3 | 0.69 | 0.69 | 0.67 | 0.78 | 0.79 | 0.53 |
| | 5 | 0.69 | 0.69 | 0.67 | 0.76 | 0.77 | 0.19 |
| | 10 | 0.68 | 0.67 | 0.66 | 0.76 | 0.79 | 0.05 |
| WC3 | 1 | 0.76 | 0.76 | 0.76 | 0.40 | 0.48 | 0.12 |
| | 3 | 0.76 | 0.76 | 0.76 | 0.16 | 0.29 | −1.07 |
| | 5 | 0.76 | 0.76 | 0.76 | 0.16 | 0.29 | −1.68 |
| | 10 | 0.76 | 0.76 | 0.75 | 0.28 | 0.44 | −1.81 |
| P1a | 1 | 0.77 | 0.77 | 0.76 | 0.39 | 0.44 | 0.48 |
| | 3 | 0.77 | 0.77 | 0.75 | 0.40 | 0.45 | 0.48 |
| | 5 | 0.77 | 0.77 | 0.75 | 0.41 | 0.46 | 0.50 |
| | 10 | 0.77 | 0.76 | 0.75 | 0.38 | 0.45 | 0.46 |
| P1b | 1 | 0.37 | 0.37 | 0.39 | −57[a] | −51[a] | −13[a] |
| | 3 | 0.37 | 0.37 | 0.38 | −65[a] | −65[a] | −35[a] |
| | 5 | 0.36 | 0.37 | 0.38 | −64[a] | −63[a] | −44[a] |
| | 10 | 0.36 | 0.37 | 0.37 | −61[a] | −60[a] | −51[a] |
| P2 | 1 | 0.83 | 0.83 | 0.80 | 0.87 | 0.86 | 0.75 |
| | 3 | 0.83 | 0.83 | 0.80 | 0.87 | 0.86 | 0.80 |
| | 5 | 0.83 | 0.83 | 0.79 | 0.87 | 0.87 | 0.86 |
| | 10 | 0.81 | 0.81 | 0.78 | 0.88 | 0.88 | 0.90 |
| W2 | 5 | 0.60 | 0.60 | 0.61 | 0.45 | 0.51 | 0.51 |
| | 10 | 0.61 | 0.63 | 0.62 | 0.45 | 0.50 | 0.45 |
| | 15 | 0.61 | 0.61 | 0.63 | 0.41 | 0.52 | 0.33 |
| | 20 | 0.61 | 0.61 | 0.63 | 0.30 | 0.40 | 0.17 |

[a] Low sediment yield and poor correlation caused exceedingly large negative N−S values.

or flowpath lengths in either channels or hillslopes due to changes in resolution did not have a significant effect on the sediment yield predictions from the watershed outlets for the Hillslope methods.

As expected, goodness of fit values ($R^2$) and Nash−Sutcliffe coefficients for the Flowpath method sediment yield simulations were lower than for the two Hillslope methods. The Flowpath method did not predict the watershed sediment yield as well as the other methods because it did not simulate channel erosion. Student T−tests that compare means showed that the Flowpath method with coarse DEM resolutions predicts higher mean values than with fine DEM resolutions.

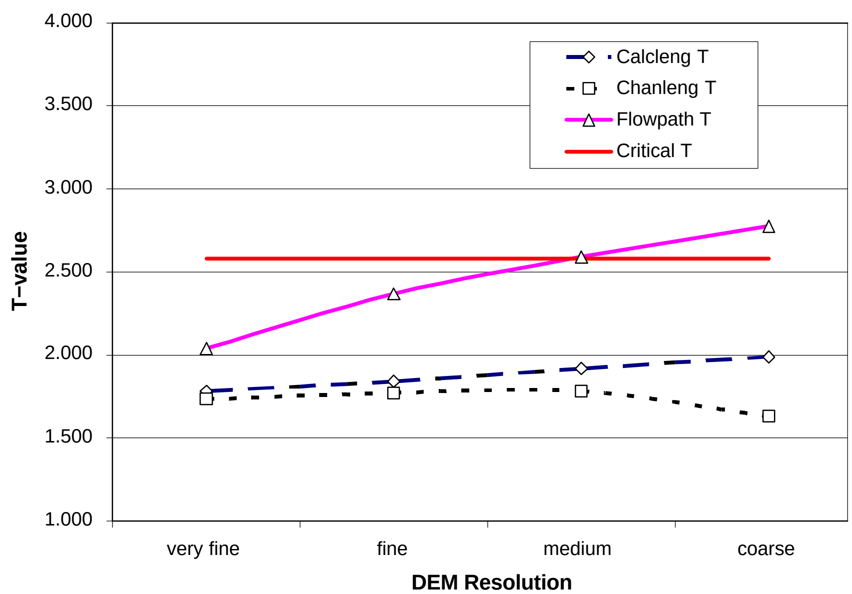


Figure 4. Comparison of means with Student test T−values between measured and simulated sediment yield events for different DEM resolutions.

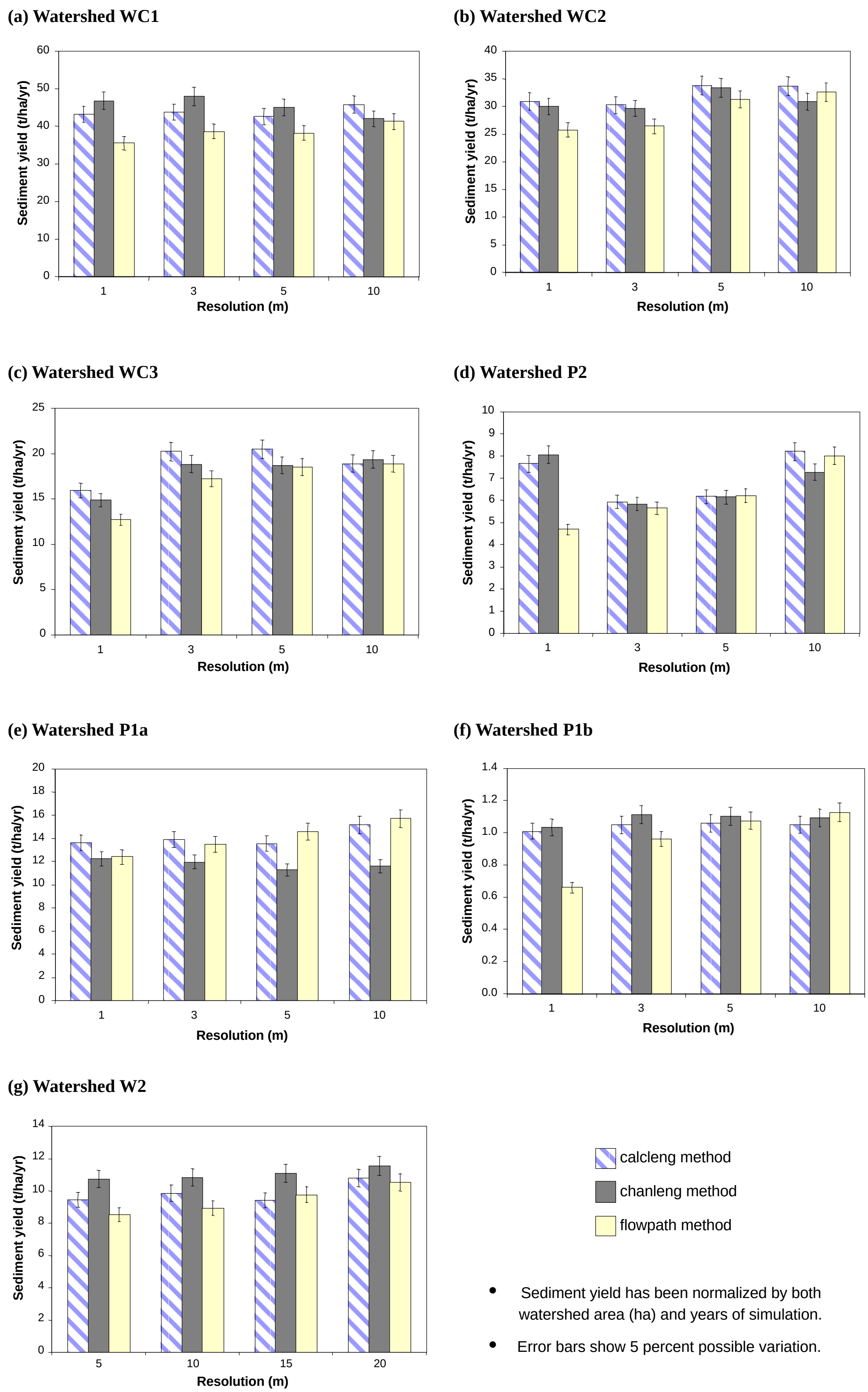


**Figure 5. Average hillslope sediment yields with three different methods and four different resolutions.**

The next portion of the analysis was thus conducted to examine if the same pattern of results was present for the different resolution levels for sediment yield and runoff from only hillslopes in the watersheds.

## Sediment Yield from Hillslopes (Delivery to Channels)

The effects of DEM resolution on the results of the simulations from only the hillslopes for both the Chanleng and Calcleng methods and Flowpath method were studied. Results for total sediment yield from the hillslopes within the watersheds are presented in figures 5a through 5g. Error bars in these graphs represent 5% possible variation that can be used to compare results between each method and resolution. Runoff results for all the watersheds varied little with DEM resolution and were consistent regardless of the method used and are thus not presented here.

For most of the watersheds, the Chanleng and Calcleng methods produced similar sediment yield predictions (fig. 5) across all resolution levels. For the Flowpath method, however, there was a consistent trend of an increase in sediment yield as the resolution became coarser. This was observed for all watersheds, but was most noticeable in the Watkinsville P2 watershed. A possible explanation for the increase in predicted sediment yield with a coarser resolution is that with the process of DEM aggregation, slope shapes are averaged out creating smoother profiles. For very fine resolutions the topography can have many small changes in slope, which can cause simulated deposition along the flowpaths, resulting in lower sediment yields. As the resolution becomes coarser, abrupt changes in elevation and slope are reduced, which in turn creates smoother flowpaths and less deposition. End slope conditions of flowpaths are also averaged out, creating a smoother delivery to the channel as the resolution becomes coarser.

Additionally, the distribution of flowpath lengths can have an effect on simulations, especially with the Flowpath method. This method runs WEPP model simulations on each flowpath, which means that it is taking into account the fact that flow does not always start at the top of a hill; it may start anywhere within the hillslope. The simulation of shorter flowpaths can reduce the overall sediment yield predictions, while the simulation of longer flowpaths can increase overall sediment yield. With finer DEM resolutions there are greater quantities of flowpaths, and their average length is generally shorter than in simulations with coarser resolutions (fig. 2). Thus, both slope and length are responsible for the increase in sediment yield predictions as resolutions become coarser in the Flowpath method. The other methods, which use the representative hillslope approach, do not seem to be affected as much because an averaging of slopes and lengths occurs to create the representative hillslope at all resolution levels (Cochrane and Flanagan, 2003).

## Soil Loss Along Profile (Hillslope Methods)

A closer look at the calculated soil loss along the representative slope profiles for each hillslope in watershed P2 provides some clues to the differences in sediment yield results due to resolution changes (fig. 6). Soil loss as calculated by the WEPP model along the representative hillslope profile varied greatly along the profile for the very fine resolution level, frequently changing from a detachment regime to a depositional mode as it approached the end of the hillslope. This can be attributed to rapid changes in slope over short distances caused by either actual topographic features

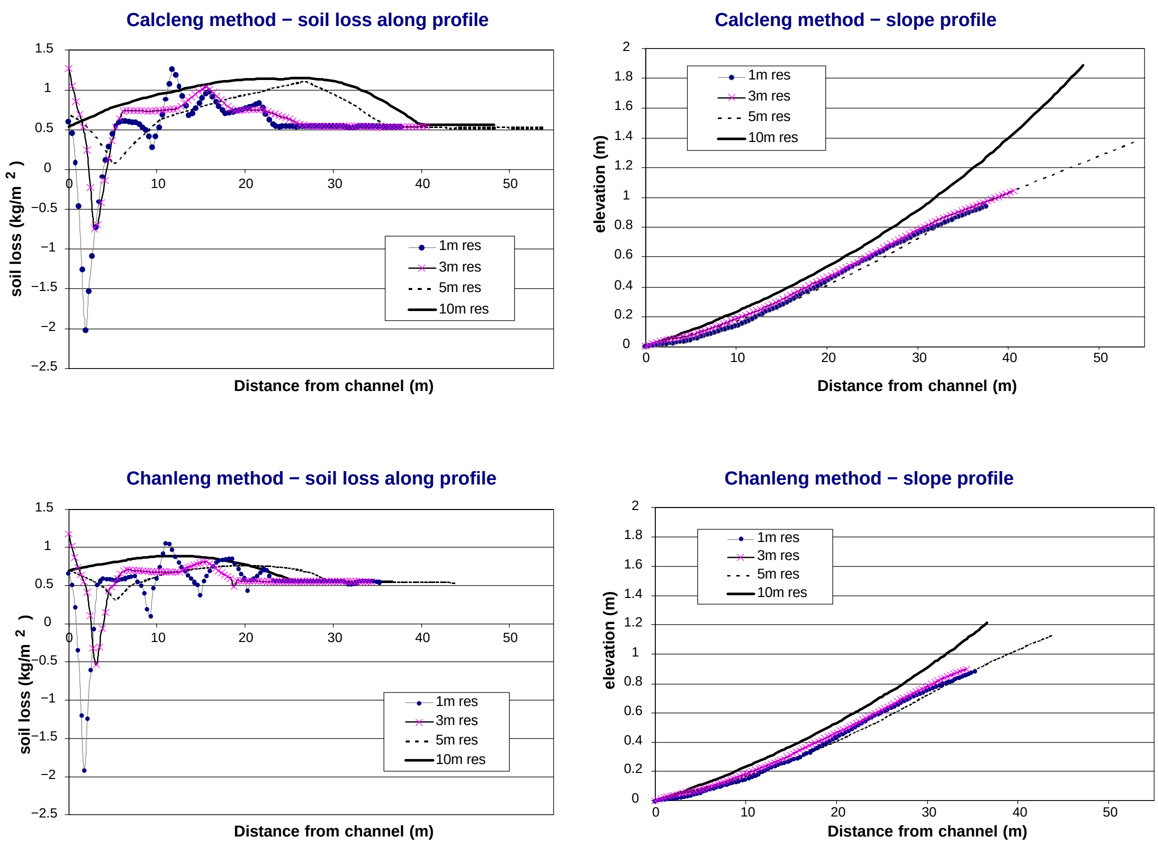


**Figure 6. Soil loss with distance and slope profile of right hillslope of Watkinsville P2 watershed for Chanleng and Calcleng methods under simulations with different DEM resolutions.**

or DEM errors due to the very fine grid resolution. As the resolution became coarser, the soil loss along the profile became more uniform. This also helps support the explanations presented earlier for the slight increase in sediment yield predictions of the Flowpath method as resolution becomes coarser.

The calculated length of the slope profiles also changed as the resolution changed for the Hillslope methods, as seen in figure 6 for the slope profiles of the right hillslope of the Watkinsville P2 watershed. The observed change in length of the representative slope profiles for the Hillslope methods is explained by the fact that the shapes and areas of these hillslopes changed as resolution became coarser. This can be readily observed in figure 1 for the hillslopes of the Watkinsville P2 watershed. The change in hillslope shape has an effect on the calculation of hillslope length because the distribution of flowpaths and lengths for that hillslope has changed. Similarly, the change in hillslope area will affect calculations of the representative profile length. Additionally, small changes in channel lengths due to resolution changes may affect the calculation of hillslope length in the Chanleng method, which uses the channel length to set the hillslope width and subsequently its length. Channels may meander more when using fine DEM resolutions. Since the algorithms developed for the Hillslope methods use flowpaths or the channel length to calculate the hillslope profile length, this length will be affected by the DEM resolution. However, as seen from the simulation exercises, the calculated hillslope length will not always increase with coarser resolutions.

### OBSERVATIONS

The results of this study lead to the observation of five important influences of DEM grid resolution on modeling with WEPP. The first is that the watershed boundary delineation is less accurate with coarser resolution data. The outline of the watershed becomes blocky and will eventually lose its original shape when the resolution is too coarse. This can be seen in figure 1 for the Watkinsville P2 watershed. The second observation is that channel networks and hillslope shapes become more difficult to define as resolution is degraded. The third observation when degrading the resolution of DEMs is that the average slope of the hillslope profiles created decreases. Soil loss either increases or decreases depending on whether the change in slope is due to removal of DEM errors that can cause areas of deposition or an overall decrease in slope. The fourth observation is that hillslope profiles become smoother as DEM resolution becomes coarser, leading to a more uniform sediment loss down the profile. Again, this can be observed in figure 6 for the left hillslope profile of the Watkinsville P2 watershed as the resolution becomes coarser. Finally, the length of flowpaths increases as resolution becomes coarser; however, the lengths of the representative slope profiles calculated by the Hillslope methods are dependent on the hillslope area and shape, which in turn are influenced by the flowpaths and channel lengths created as a function of the resolution.

### INTERACTIONS BETWEEN RESOLUTION AND EVENT SIZES

Mean values, goodness of fit values ($R^2$), and Nash−Sutcliffe model efficiency coefficients for measured versus predicted sediment yield for the interaction between resolution and rainfall event size are presented in table 7. For all methods and resolutions, simulation of larger rainfall events produced successively better linear regression fits ($R^2$) than simulation of smaller events, as was expected according to Nearing (1998). Nash−Sutcliffe model efficiency coefficients showed that sediment yields during very large rainfall events were better predicted than during large, medium, or small events. For the large rainfall event range, the predicted values were substantially larger than the measured values, as evidenced by the negative N−S model efficiencies. Both $R^2$ values and N−S coefficients showed that very fine resolutions did not predict better results than coarse resolutions for small rainfall events.

**Table 7. Means, goodness of fit ($R^2$), and Nash−Sutcliffe coefficients (N−S) between measured and simulated sediment yield values for the interactions between resolution and rainfall event sizes.**

| DEM | | Small Events | | | Medium Events | | | Large Events | | | Very Large Events | | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Res. | Method | Mean[a] | $R^2$[b] | N−S | Mean | $R^2$ | N−S | Mean | $R^2$ | N−S | Mean | $R^2$ | N−S | ($R^2$) |
| Very fine | Calcleng | 0.025 | 0.12 | 0.10 | 0.155 | 0.28 | 0.17 | 0.667 | 0.51 | −3.47 | 1.152 | 0.86 | 0.84 | 0.441 |
| | Chanleng | 0.024 | 0.12 | 0.10 | 0.153 | 0.25 | 0.14 | 0.670 | 0.49 | −3.73 | 1.133 | 0.87 | 0.86 | 0.431 |
| | Flowpath | 0.041 | 0.10 | 0.08 | 0.206 | 0.23 | −0.36 | 0.868 | 0.49 | −10.15 | 1.152 | 0.86 | 0.69 | 0.418 |
| | Combined | 0.03 | 0.11 | 0.10 | 0.171 | 0.25 | 0.03 | 0.735 | 0.50 | −5.43 | 1.145 | 0.88 | 0.84 | 0.433 |
| Fine | Calcleng | 0.028 | 0.15 | 0.13 | 0.159 | 0.30 | 0.19 | 0.688 | 0.52 | −3.79 | 1.160 | 0.85 | 0.83 | 0.454 |
| | Chanleng | 0.026 | 0.16 | 0.12 | 0.157 | 0.28 | 0.17 | 0.689 | 0.51 | −4.00 | 1.133 | 0.86 | 0.84 | 0.450 |
| | Flowpath | 0.047 | 0.14 | 0.12 | 0.224 | 0.24 | −0.51 | 0.974 | 0.52 | −13.12 | 1.267 | 0.83 | 0.51 | 0.433 |
| | Combined | 0.033 | 0.15 | 0.14 | 0.180 | 0.27 | 0.02 | 0.784 | 0.52 | −6.39 | 1.187 | 0.86 | 0.79 | 0.448 |
| Medium | Calcleng | 0.029 | 0.11 | 0.10 | 0.163 | 0.28 | 0.15 | 0.699 | 0.52 | −3.92 | 1.180 | 0.86 | 0.84 | 0.444 |
| | Chanleng | 0.027 | 0.14 | 0.12 | 0.157 | 0.26 | 0.14 | 0.691 | 0.52 | −3.86 | 1.132 | 0.87 | 0.86 | 0.446 |
| | Flowpath | 0.049 | 0.12 | 0.08 | 0.238 | 0.25 | −0.64 | 1.039 | 0.53 | −14.84 | 1.365 | 0.85 | 0.41 | 0.436 |
| | Combined | 0.035 | 0.12 | 0.12 | 0.186 | 0.26 | −0.04 | 0.810 | 0.53 | −6.78 | 1.226 | 0.87 | 0.79 | 0.445 |
| Coarse | Calcleng | 0.031 | 0.12 | 0.11 | 0.171 | 0.29 | 0.11 | 0.700 | 0.51 | −4.04 | 1.205 | 0.86 | 0.83 | 0.445 |
| | Chanleng | 0.030 | 0.14 | 0.12 | 0.158 | 0.30 | 0.20 | 0.634 | 0.48 | −2.98 | 1.101 | 0.86 | 0.85 | 0.443 |
| | Flowpath | 0.056 | 0.15 | 0.10 | 0.259 | 0.24 | −0.98 | 1.099 | 0.53 | −17.37 | 1.453 | 0.85 | 0.25 | 0.442 |
| | Combined | 0.039 | 0.14 | 0.14 | 0.196 | 0.27 | −0.10 | 0.811 | 0.51 | −6.96 | 1.253 | 0.87 | 0.77 | 0.449 |
| Measured data | | 0.07 | 1 | 1 | 0.167 | 1 | 1 | 0.197 | 1 | 1 | 0.845 | 1 | 1 | 1 |

[a] Mean values in T/ha/event.
[b] $R^2$ is a goodness of fit value in a linear regression between measured and simulated events.

An analysis of mean sediment yield from the watershed outlets showed that there were observable interactions between event sizes and resolution. Table 7 shows that there is an observable increase in predicted mean values from very fine to coarse resolutions for all simulations. In figure 7, we present a comparison of the ratio of mean sediment yield between very fine and coarse DEM resolution simulations for the four event size ranges, which shows whether there is a greater or lesser variance between very fine and coarse resolution associated with the event size. For example, the ratio between differences in simulation between the very fine and coarse resolution for small events is 0.030/0.039 = 0.77, or 77%, whereas this same ratio for very large events is 1.145/1.253 = 0.91, or 91%, for the combined methods. These results indicate that for large events, very fine or coarse resolutions predict mean sediment values equally well, whereas predictions of small events are more dependent on resolution size. In general, it was also observed that simulated mean sediment yield was less than measured values for small events, but for large events, simulated mean sediment yields were larger than measured values, even though coarser resolutions predicted higher mean sediment yield values than finer resolutions.

## Summary and Conclusions

The results of this study showed that in general WEPP erosion model simulations with the two Hillslope methods using fine resolution DEMs did not predict runoff or soil loss significantly better than simulations using coarser resolutions. This finding that a wide range of DEM resolutions can be used for runoff and sediment yield simulations from the watershed outlet and hillslopes is important because it implies that it may not be necessary to produce costly, fine−resolution DEMs for the application of our current erosion models, at least to estimate runoff and sediment yield at the watershed outlet. A basic rule of thumb for selecting the appropriate DEM resolution for erosion modeling can therefore be established as follows. If the user is only interested in sediment yield from hillslopes or the watershed outlet, coarse resolutions may work as well as finer ones. However, if the watershed channel network, boundary, or hillslope shapes are compromised or become significantly different from the original watershed, then the resolution is too coarse. If the user is interested in results of soil loss within the hillslope profile, then finer resolutions are better, as long as the fine resolutions accurately represent the hillslope or watershed topography.

The study of the degradation of DEM resolution showed that the average length and proportion of longer flowpaths increased as the resolution became coarser, and mean values of the predictions of sediment yield increased, particularly for the Flowpath method, even though mean and maximum slopes decreased. This was something that was not obvious but may be very important when modeling soil erosion using DEMs with either representative profiles in the Hillslope methods or flowpaths in the Flowpath method. The procedures may be overpredicting soil loss because they may not be adequately taking into account that flow does not always start at the top of the hillslope.

The results of the study of the interactions between resolution and rainfall event sizes are also important. They indicate that the very large events were better predicted than the large, medium, or small rainfall events. Predictions of mean sediment values increased with coarser resolutions. However, when compared to measured values, mean sediment yield values were overpredicted for large events and underpredicted for small rainfall events. There was also a greater variance of predictions of mean sediment yield between very fine and coarse resolutions for smaller event

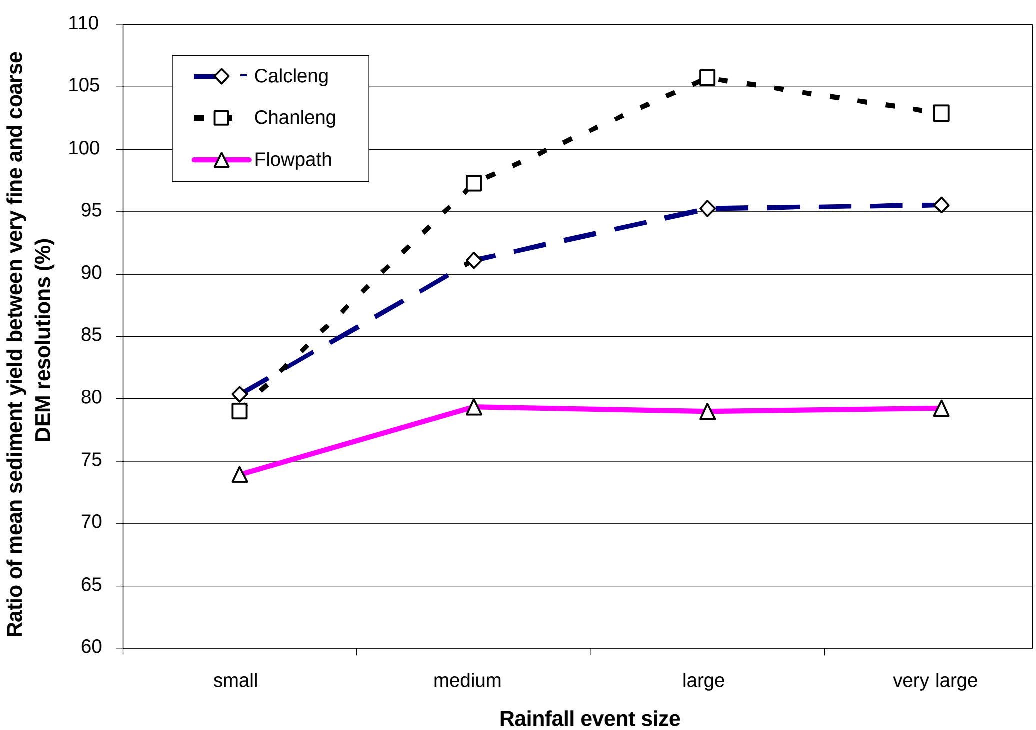


**Figure 7. Variations in predictions of mean sediment yield between very fine and coarse DEM resolutions for different rainfall event sizes.**

sizes than for larger event sizes, which indicates that resolution has a greater influence on the prediction of mean sediment yield for smaller rainfall events than for larger events.

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